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THE FAINTNESS OF THE 158 μM [C II] TRANSITION IN THE Z=6.42 QUASAR SDSS J1148+5251

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ABSTRACT

We report the non-detection of the [C II] ($^2P_{3/2} \rightarrow ^2P_{1/2}$) 157.74 μm transition in the $z = 6.42$ quasar SDSS J1148+5251 after 37.5 hours of integration with the James Clerk Maxwell Telescope. This transition is the main cooling line of the star-forming interstellar medium, and usually the brightest FIR line in galaxies. Our observed 1 σ RMS = 1.3 mK in the T_A^* scale translates to $L_{[CII]} < 2.6 \times 10^9$ $L_\odot$. Using a recent estimate of the far-infrared continuum of this quasar, we derive for SDSS J1148+5251 $L_{[CII]}/L_{FIR} < 5 \times 10^{-4}$, a ratio similar to that observed in local ultra-luminous infrared galaxies but considerably smaller than what is typical in nearby normal and starburst galaxies. This indicates that the small $L_{[CII]}/L_{FIR}$ ratio observed locally in luminous far-infrared objects also persists at the highest redshifts.

Subject headings: quasars: individual (J114816.64+525150.3) — quasars: emission lines — early universe — radio lines: galaxies

1. INTRODUCTION

The most distant quasar in the universe known at the time of this writing is SDSS J114816.64+525150.3 (hereafter SDSS J1148+5251) at a redshift $z = 6.42$ (Fan et al. 2003; Walter et al. 2003; Bertoldi et al. 2003a). With a bolometric luminosity of $L_{bol} \sim 10^{14}$ $L_\odot$, this is an extremely luminous object powered by a $\sim 3 \times 10^9$ $M_\odot$ supermassive black hole at its core (Willott et al. 2003). The high far-infrared (FIR) luminosity of this object implies that the host galaxy is forming stars at the prodigious rate of 3000 $M_\odot$ yr^{-1} (Bertoldi et al. 2003b). At this redshift the universe is only 840 million years old and both the black hole mass and star formation rate imply the existence of a very massive galaxy formed from one of the rarest high-density peaks in the matter distribution. Although there are hints that SDSS J1148+5251 may be weakly gravitationally lensed (White et al. 2003), we assume no lensing magnification in this paper.

The recent detection of bright molecular and FIR continuum emission from the host galaxy of SDSS J1148+5251 (Walter et al. 2003; Bertoldi et al. 2003a; Bertoldi et al. 2003b) prompted us to observe the [C II] ($^2P_{3/2} \rightarrow ^2P_{1/2}$) 157.74 μm fine structure transition in this object. This is the main cooling transition of the star-forming interstellar medium (e.g., Tielens & Hollenbach 1985), and is commonly the single brightest emission line in galaxies. For example, Stacey et al. (1991) found that most galaxies emit 0.1% to 1% of their far-infrared luminosities in this line alone.

Given its extremely high luminosity and its relationship to star formation activity, the redshifted [C II] 158 μm transition is attractive as a star formation indicator at high-z (e.g., Stark 1997). This transition is conveniently placed into the atmospheric 1 mm window for redshifts $z \gtrsim 6.2$, making it accessible to ground-based instrumentation. Furthermore, a spectroscopic approach to detecting high-z sources has the clear advantage of containing redshift information, unlike continuum observations, thus avoiding problems of source confusion that stem from the low angular resolution of single-dish radio telescopes equipped with bolometer arrays. As early as 1997, however, Infrared Space Observatory (ISO) observations suggested potential problems with this method. Indeed, Malhotra et al. (1997) and Luhman et al. (1998) found that the proportionality between the [C II] and FIR continuum luminosities observed in nearby star forming galaxies broke down for luminous infrared galaxies, where the [C II] luminosity appeared not to exceed $L_{[CII]} \sim 10^9$ $L_\odot$. These conclusions, confirmed and expanded in a recent analysis of ISO data by Luhman et al. (2003), have since cast doubts on the usefulness of redshifted [C II] to probe star formation in the distant universe. The observations presented here have bearing on this matter: does the paucity of [C II] emission observed in local ultra-luminous infrared galaxies (ULIRGs) hold for objects in the early universe?

2. OBSERVATIONS AND RESULTS

We observed the quasar SDSS J1148+5251 using the James Clerk Maxwell Telescope (JCMT) at Mauna Kea, Hawaii[1]. The observations were performed in the flexible queue mode over several shifts between 2003 Novem-

[1] The JCMT is operated by the Joint Astronomy Centre in Hilo, Hawaii on behalf of the parent organizations Particle Physics and Astronomy Research Council in the United Kingdom, the National Research Council of Canada and The Netherlands Organization for Scientific Research.

ber 15 and 2004 January 30, using 8 Hz beam-position switching over 60 second cycles with offsets of 60″ in azimuth. Standard calibration observations, which include pointing and focus, were performed at the beginning and sometimes near the end of each shift. The RxA3 dual sideband heterodyne receiver of the JCMT was tuned to place 256.172 GHz at the center of the lower sideband, which assumes a rest frame wavelength for the [C II] transition of $\lambda = 157.74$ μm and a redshift of $z = 6.419$ as reported for the CO detections of this object (Walter et al. 2003; Bertoldi et al. 2003a). We utilized the 1840 MHz bandpass of the Digital Autocorrelation Spectrometer which allowed us to cover a velocity range approximately ± 1100 km s^{-1} around the expected emission, equivalent to a redshift range $z \approx 6.39 - 6.44$ (by comparison, the detected CO lines are $\sim$ 300 km s^{-1} wide). Approximately 48 hours of integration were devoted to this project.

Individual spectra obtained from 10 minute-long integrations were read into SPECX, merged, and converted to FITS format. The data were then read into COMB where spectra showing abnormal RMS (due to baseline problems) were expunged, and good quality individual integrations were then combined using the built-in weighting scheme (i.e., t_{int}/T^2_{sys}), then Hanning-smoothed to 10 MHz wide channels. The final spectrum is shown in Figure 1, the result of 37.5 hours of integration after the removal of a linear baseline. Its RMS is 1.3 mK in the central 1000 km s^{-1} region, or 32 mJy assuming an aperture efficiency ≈ 0.56 for the JCMT at the observing frequency. The integrated intensity of the [C II] line is $\mathrm{I_{[CII]}} \approx -1.7 \pm 1.9$ Jy km s^{-1} $\approx (-1.4 \pm 1.6) \times 10^{-17}$ erg s^{-1} cm^{-2}. The calibration uncertainty of these observations could be as large as 30% due to the poorly characterized sideband ratio of RxA3 at 256 GHz combined with the complex frequency structure of the receiver noise temperature.

To convert this measurement to a luminosity in a manner consistent with other recent work on this source, we adopt the WMAP cosmology with $\mathrm{H_0} = 71$ km s^{-1}, $\Omega_\mathrm{m} = 0.27$, and $\Omega_\Lambda = 0.73$ (Spergel et al. 2003). The luminosity distance to a source at a redshift $z = 6.419$ is then $D_l \approx 1.97 \times 10^{29}$ cm. Consequently, the [C II] luminosity of SDSS J1148+5251 is $\mathrm{L_{[CII]}} < 2 \times 10^9$ $\mathrm{L_\odot}$. Using the FIR luminosity $\mathrm{L_{FIR}} \approx 1.2 \times 10^{13}$ $\mathrm{L_\odot}$ determined by Bertoldi et al. (2003b) from 1 mm continuum observations carried out with the MAMBO array, the [C II]/FIR ratio is $\mathrm{L_{[CII]}/L_{FIR}} < 1.7 \times 10^{-4}$. Taking into account that changing the assumed 40 K dust temperature by ± 10 K will change the derived $\mathrm{L_{FIR}}$ by a factor of 2 (Bertoldi et al. 2003b) and the aforementioned uncertainties in the [C II] calibration, a more conservative limit is $\mathrm{L_{[CII]}/L_{FIR}} < 5 \times 10^{-4}$.

3. DISCUSSION

The limit obtained on the [C II] emission in J1148+5251 confirms some of the suggested caveats on the usefulness of redshifted [C II] emission as a beacon for star formation in the early universe. The [C II] line in this very luminous FIR object is disproportionally faint. Indeed, our limit suggests a ratio in this quasar that appears typical of the local sample of 15 ULIRGs studied by Luhman et al. (2003). Their analysis found a median [C II]/FIR flux ratio of $\mathrm{F_{[CII]}/F_{FIR}} = 3.9 \times 10^{-4}$ in ULIRGs whereas a median $\mathrm{F_{[CII]}/F_{FIR}} = 3.1 \times 10^{-3}$ was reported for a sample of 60 normal star-forming galaxies by Malhotra et al. (2001). Only one in five ULIRGs approached the lower end of the distribution of [C II]/FIR ratios found in normal galaxies, with $\mathrm{F_{[CII]}/F_{FIR}} \sim 10^{-3}$. The [C II] luminosities of the ULIRG systems studied by Luhman et al. had a mean value $\mathrm{L_{[CII]}} \sim 1 \times 10^9$ $\mathrm{L_\odot}$ with none exceeding 3.5×10^9 $\mathrm{L_\odot}$. If the brightest [C II] luminosities that can be expected from objects at $z \sim 6.5$ were similar to the luminosities of local ULIRGs, observations that probe such regime need to be $\sim 3-10$ times more sensitive than what we have acheived — a feat probably beyond the current reach of single-dish instruments but which may be attainable by the IRAM Plateau de Bure Interferometer or certainly by the future Atacama Large Millimeter Array.

What are the reasons behind the deficit of [C II] emission relative to the FIR continuum? Malhotra et al. (1997; 2001) find a strong correlation between decreasing $\mathrm{L_{[CII]}/L_{FIR}}$ ratio and increasing $\mathrm{L_{FIR}}$ and FIR color temperature, indicating a smooth transition between the ratio observed in normal luminosity galaxies and that in ULIRGs, which in turn suggests that the same mechanism is responsible for low ratios in both types of objects. Indeed, about 7% of the sources in the Malhotra et al. (2001) sample have measured ratios or limits that are smaller than the $\mathrm{L_{[CII]}/L_{FIR}} \sim 5 \times 10^{-4}$ more typical of ULIRGs, although their luminosities are $\mathrm{L_{FIR}} \sim 10^{10} - 10^{11}$ $\mathrm{L_\odot}$. The physical conditions of the gas in SDSS J1148+5251 may hold clues as to what mechanism is responsible for the low observed ratios. For example, we can place this object in the [C II]/FIR vs. CO/FIR plots obtained from photodissociation region (PDR) models (e.g., see Kaufman et al. 1999) using our limit and the CO observations and estimate some of its physical parameters. The observational limit for the luminosity of the CO ($1 \rightarrow 0$) transition in SDSS J1148+5251 reported by Bertoldi et al. (2003a) is $\mathrm{L_{CO}} < 7 \times 10^6$ $\mathrm{L_\odot}$, which yields $\mathrm{L_{CO}/L_{FIR}} < 6 \times 10^{-7}$. Their multitransition LVG analysis, however, suggests that the excitation conditions of the CO are very similar to those found by Bradford et al. (2003) in the starburst galaxy NGC 253. The expected CO ($1 \rightarrow 0$) luminosity would then be close to the the observational limit, i.e., $\mathrm{L_{CO}/L_{FIR}} \sim 6 \times 10^{-7}$. Using Fig. 16 of Kaufman et al. we can infer a UV radiation field strength $G_0 \gtrsim 600$ in units of the local interstellar radiation field (Habing 1968), and densities $n \gtrsim 10^5$ cm^{-3}. In this determination the CO/FIR ratio constrains the radiation field, while the [C II]/FIR ratio constrains the gas density. A PDR with an incident radiation field $G_0 \gtrsim 600$ would have a surface temperature $T \sim 200$ K, rapidly decreasing as the gas becomes increasingly molecular. These conditions are actually not peculiar, and are very similar to those found in a variety of starburst galaxies and Galactic star-forming regions (Stacey et al. 1991).

Whether or not a simple analysis like that described above can be applied with impunity to a complex system such as an AGN is debatable. Based on their available data, Malhotra et al. (1997; 2001) and Luhman et al. (2003) concluded that the observed deficit of [C II] emission relative to the continuum emission in FIR-luminous

objects is consistent with: 1) low [C II] emission arising from PDRs with high G_0/n, and/or 2) excess FIR emission not related to PDRs, but perhaps arising from a enshrouded AGN component. In the first case, the conversion of UV photons into electrons that heat the gas is inefficient because the dust grains rapidly become positively charged and their photoelectric yield is dramatically reduced. Thus, the gas temperature (and with it the [C II] brightness) does not increase proportionally with the radiation field but the dust temperature still does, leading to low $L_{[CII]}/L_{FIR}$ ratios. In the second case, the [C II] emission related to the AGN core is quenched for much the same reasons, as well as because most of the carbon will likely be in a higher ionization state. Copious FIR radiation will be generated, however, if the AGN is at least partially embedded in a dusty envelope. Although this latter scenario naturally explains the deficit of [C II] emission in a quasar, we caution that there is a dearth of additional evidence for it. For example, one may expect that an excess of FIR emission associated with dust near the ionized core of the AGN will result in a lower than usual L_{CO}/L_{FIR} ratio. The $L_{CO}/L_{FIR} \sim 6 \times 10^{-7}$ ratio inferred for SDSS J1148+5251, however, is unremarkable when compared to a sample of local starburst galaxies and Galactic star-forming regions (Stacey et al. 1991). Indeed, this quasar falls into a region of the $I_{[CII]}/I_{FIR}$ vs. I_{CO}/I_{FIR} space mostly occupied by ULIRGs (see Fig. 8a of Genzel & Cesarsky 2000), showing that the observed ratios are not peculiarly associated with AGN activity. Nevertheless, without a detection of the CO ($1 \rightarrow 0$) transition or a stronger limit, it is difficult to develop this analysis any further.

4. SUMMARY AND CONCLUSION

Our redshifted [C II] observations at $\nu \sim 256$ GHz have failed to detect the fine structure 158 μm [C II] transition in this high-z quasar. We place a 1 σ limit on the [C II] luminosity of SDSS J1148+5251 of $L_{[CII]} < 2.6 \times 10^9$ $L_\odot$ (including 30% calibration uncertainty). Given the observed FIR flux of this source, this places an upper limit on its [C II] to FIR ratio of $L_{[CII]}/L_{FIR} < 5 \times 10^{-4}$, substantially lower than what is found in most local star-forming galaxies but similar to what is observed in nearby ultra-luminous IR galaxies. If the cause of this [C II] deficit in SDSS J1148+5251 was a large FIR component due to partial dust reprocessing of the AGN radiation, thus unrelated to star formation activity, the $\sim$3000 $M_\odot$ yr^{-1} star formation rate obtained from the FIR continuum could be a substantial overestimate. Obtaining a better SED for the FIR continuum emission, to constrain better the FIR luminosity, as well as improving the sensitivity of the CO ($1 \rightarrow 0$) observations, may help to elucidate this matter.

Will redshifted [C II] observations open a new window onto high-z galaxies? Our results are based on observations of just one object at high redshift. A larger sample of $z > 6$ sources with high FIR luminosities must be observed in the [C II] transition to establish whether low $L_{[CII]}/L_{FIR}$ ratios are a general phenomenon. If a maximum luminosity $L_{[CII]} \sim 10^9$ $L_\odot$ were confirmed for most sources, the Atacama Large Millimeter Array would still be able to detect the [C II] line and spatially resolve its distribution and kinematics. The answer, then, is a hopeful *yes*.

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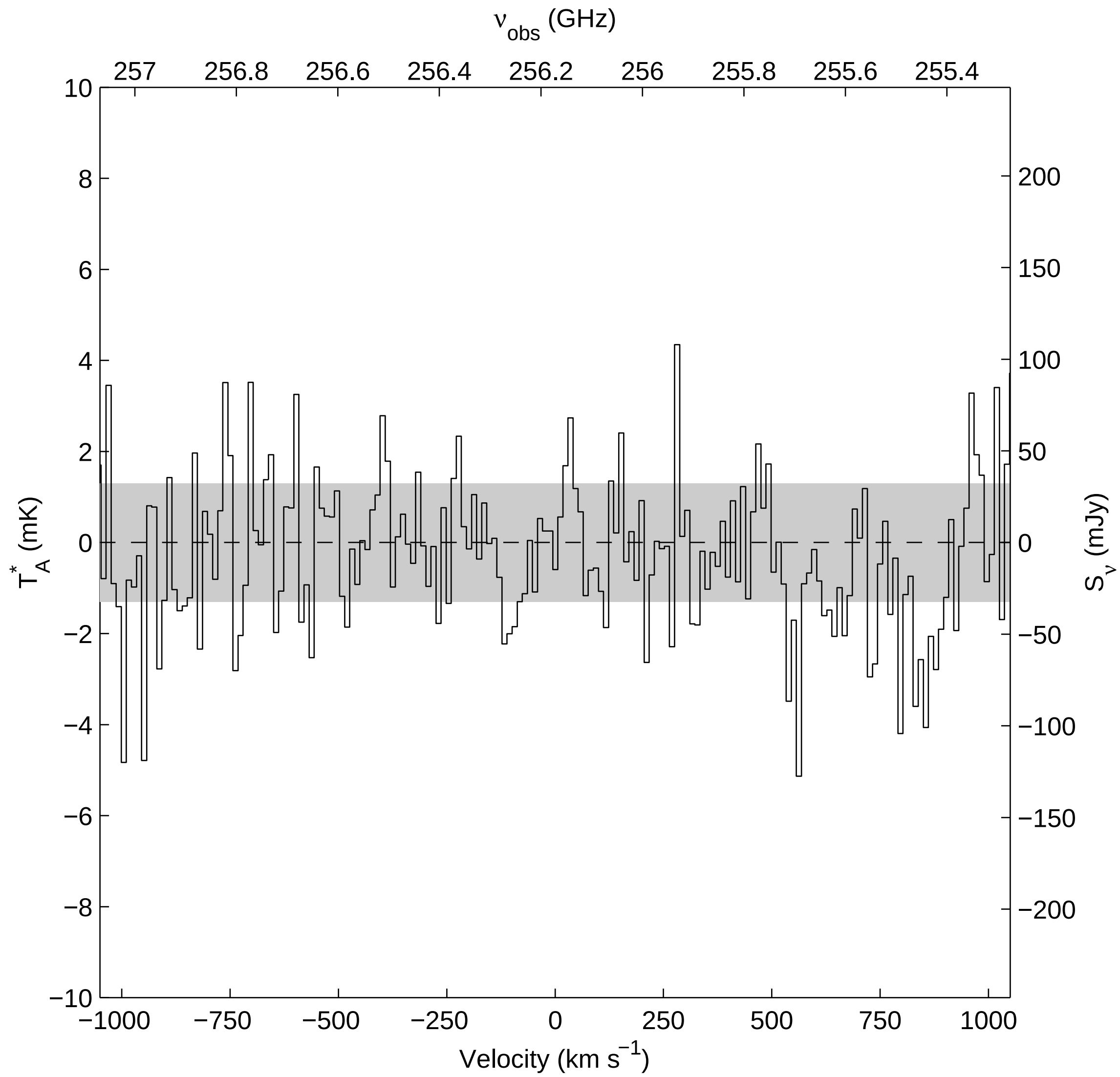

FIG. 1.— The redshifted [C II] spectrum obtained at the JCMT, with a total of 37.5 hours of integration. The RMS in 10 MHz wide channels ($\sim$ 11 km s^{-1}) in the central 1000 km s^{-1}, illustrated by the gray region, is 1.3 mK in the T_A^* scale. This corresponds to $\approx$ 32 mJy, using an aperture efficiency $\eta_{ap} \sim 0.56$.